A Microwave Frequency Distribution Technique for Ultrastable Standard Frequencies

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A radio distribution system is needed which allows for distribution of stable reference frequency standards, such as those from the hydrogen maser, over long distances (inter-site) without degrading the stability of the frequency standard. The distribution systems described here are two-way radio links that compute the change in path length and correct the phase of the transmitted signal such that the phase of the signal arriving at the remote site is independent of perturbations in the path linking the two sites.

I. Introduction

Distribution of stable frequencies over one-way radio links longer than a few hundred meters is not possible without degradation of the stability of the frequency. For example, a 50-km path has a stability of about 1.7×10^{-10} (reference = NRL RPT 7140). This stability would completely mask the 10^{-14} stability of a hydrogen maser frequency standard. If radio links are to be employed for frequency distribution, some method of correction must be employed. One such method is to use a two-way link, which can automatically adjust the phase of the transmitted signal from the master station such that the phase at the remote station remains constant. The return link transmits the signal received by the remote station back to the master station, allowing the master station to determine the change in propagation time of the path and correct the transmitted phase such that no change in the phase of the signal received at the remote station is observed.

II. Basic System Concept

The basic concept of the frequency distribution system is shown in Fig. 1a. A frequency $\omega \underline{/\omega\tau}$ is transmitted from the master site to the remote site. After encountering a delay of τ, the phase of the received signal is $\omega \underline{/0}$, the reference frequency to be distributed, at the reference phase angle. This signal is then returned to the master station, where the phase is $\omega \underline{/-\omega\tau}$. By forcing the transmitted signal to lead the reference phase by the same amount that the received signal lags the reference phase, correction for perturbations in the path can be effected. This whole system is predicated on reciprocity of the path. If τ is different for the two directions, it will be impossible to obtain proper correction. Any equipment that is common to both transmit and receive functions (coax, waveguide, antennas, etc.) will be considered part of the path and will be corrected. Any phase shifts that are not reciprocal will appear directly at the output of the remote site.

III. Practical Circuit Considerations

The circuit shown in Fig. 1a shows conceptually the operation of a self-correcting distribution system. There are, however, practical problems with the configuration shown in Fig. 1a. The most obvious problem is that the transmitter and receiver at each site are operating at the same frequency. A practical circuit would, therefore, be required to operate at different transmit and receive frequencies. The use of different operating frequencies requires additional synthesis before a phase comparison between transmitted and received phases can be made without error. Figure 1b shows the transmitted and received phases being compared. As can be seen, the transmit phase ω_T is being forced to equal the received phase $K\omega_T$. This will result in a phase error at the receiving end, i.e., some correction for the path will be made; however, there will be some phase error. If K is near one, this error will be small and will be able to provide corrections adequate to distribute standards with stabilities of 10^{-15} without severe degradation. Figure 1c shows a system that corrects for the different frequencies being used. This system simply multiplies the received signal by $1/K$. Beyond this point operation is identical to the system discussed in Fig. 1a. The problem with the system shown in Fig. 1c is that K is not always an integer. For example, in one system under consideration $K = 84001/84000$, a nontrivial synthesis.

An additional problem with the configuration shown in Fig. 1c is the use of separate phase comparators for the transmit and receive phase versus the master frequency standard. This system would require exactly matched phase detectors, which is a problem, although possible if they are not required to track over large regions. Over long paths, with high frequency or microwave links, many cycles of phase may change, requiring the phase detectors to track over a complete cycle—a difficult requirement to meet. Figure 1d shows an alternative system that eliminates the aforementioned difficulty. The transmit signal is mixed with twice its frequency, yielding the same frequency with opposite sign on the phase. This signal can be compared to the received signal in a single phase detector with the received signal. This phase detector will always be operating at or very near 0-deg phase error. Figure 1d is still a conceptual circuit and should not be construed to be a proposal for an actual circuit.

IV. An Exact Synthesis System

The details of the operation may be understood by referring to the block diagrams of Figs. 2a and b.

The transmitter voltage-controlled oscillator (VCO), operating at $\omega_s \underline{/\theta_s}$ ($\approx$8400.1 MHz), is used to send a signal to the receiver at the remote site, where it is received with a time delay T; thus, the received signal is $\omega_s \underline{/\theta_s - \omega_s T}$. The receiver local oscillator (LO) signal is phase-locked to the signal with an offset of -100 kHz, which is derived (along with all the other standard frequencies of 1, 5, 10, and 100 MHz) from the receiver VCO. This LO signal is also transmitted back to the transmitter. The signal leaves the receiver as

$$\omega_s \frac{84000}{84001} \underline{/(\theta_s - \omega_s T) \frac{84000}{84001}}$$

as is seen by examining the operation of the receiver system. This signal arrives at the transmitter with an additional time delay T, so that the signal received at the transmitter is

$$\omega_s \frac{84000}{84001} \underline{/(\theta_s - 2\omega_s T) \frac{84000}{84001}}$$

where it is mixed with the original transmitted signal to give an intermediate frequency (IF) of

$$\omega_s \frac{1}{84001} \underline{/(\theta_s + 2\omega_s T) \frac{84000}{84001}}$$

(This is written differently in the block diagram, but $N = 84000$ on this diagram, so the two ways of writing it are equivalent.) At the transmitter, the reference frequency $\omega_0 \underline{/0}$ (taken as 100 MHz from the hydrogen maser) is multiplied by 84 and mixed with the transmitter VCO to give an IF reference of $\omega_s/84001 \underline{/\theta_s}$ (100 kHz) if we use the fact that

$$\omega_s = \omega_0 \frac{84000}{84001}$$

This IF reference is then operated on by a synthesizer, which in effect multiplies it by

$$\frac{2N+1}{N+1} = \frac{168001}{84001}$$

producing a signal

$$\frac{2N+1}{(N+1)^2}\,\omega_s \underline{/\theta_s \frac{2N+1}{N+1}} \approx 200\ \text{kHz}$$

This is mixed with another reference frequency

$$\frac{10\omega_s}{N+1} = 1\ \text{MHz}$$

to produce

$$\frac{10\omega_s}{N+1} + \frac{2N+1}{(N+1)^2}\,\omega_s \underline{/\theta_s \frac{2N+1}{N+1}} \approx 1.2\ \text{MHz}$$

which is then mixed with another signal,

$$\frac{10\omega_s}{N+1}\underline{/0} + \frac{N\omega_s}{(N+1)^2}\underline{/0} \approx 1.1\ \text{MHz}$$

which has been synthesized from the

$$\frac{10\omega_s}{N+1}\underline{/0} = 1\ \text{MHz}$$

and

$$\frac{100\omega_s}{N+1}\underline{/0} = 10\ \text{MHz}$$

reference frequencies. The result of all this synthesis and mixing is the signal which is used as the local reference for the phase detector. This signal,

$$\frac{\omega_s}{N+1}\underline{/\theta_s \frac{2N+1}{N+1}}$$

is subtracted from the IF of

$$\frac{\omega_s}{N+1}\underline{/\theta_s \frac{1}{N+1} + 2\omega_s T \frac{N}{N+1}}$$

giving zero frequency and phase of

$$\underline{/\frac{2N}{N+1}(\omega_s T - \theta_s)}$$

Under the usual assumptions for phase-locked loops (δ small such that $\sin \delta \cong \delta$), the output of the phase detector is then

$$K_d \frac{2N}{N+1}(\omega_s T - \theta_s)$$

Since the phase gain of the loop is infinite at zero frequency, the output of the phase detector is constrained such that $\phi \equiv 0$; therefore, $\omega_s T = \theta_s$.

Under these conditions, the receiver at the remote site receives (and retransmits) a signal which has the same phase as the reference. In the proposed system for Goldstone, the total time delay will be $\approx$10 ms. Such perturbations of the time delay will, of course, cause variations in phase, but *only at times corresponding to this round-trip delay or shorter.* For such short times the phase-locked loop will have low gain, and the receiver VCO will give the main control over phase. In other words, for long time stability down to $<$0.1 s, the output phase of the receiver will be determined by the transmitter, while for short term, the phase will be determined by the receiver (crystal) VCO; this is identical to the situation in the original hydrogen maser signal.

There are, of course, innumerable ways to implement such a system. This particular one is being considered for several reasons:

(1) To ensure good spectral characteristics, no synthesis is performed on signals which are multiplied to X-band.

(2) To reduce development and implementation costs, maximum use is made of components which have already been developed for the hydrogen maser.

(3) All complicated synthesis is done at the transmitter, thus allowing a great many of the synthesized signals to be used for several transmitters, further reducing costs.

(4) The operating frequency (8.4 GHz) lies in a very low dispersion region in the spectrum and is also an unused area in the DSN microwave communications link.

V. Approximate System

As can be seen in the previous section, the exact synthesis scheme requires a relatively complex synthesizer. An alternative approach is to use an approximate system that will allow substantial, though not complete, corrections for perturbations in the path. Figure 3 shows an approximate system under study in this section. This system will provide a path stability improvement of about 1.7×10^5. Such an improvement should allow an overall stability of about 10^{-15} over a 50-km path.

VI. Time Synchronization

By using suitable modulation/demodulation schemes, time signals may be impressed on the signals to allow time synchronization between sites to a level $\approx$10 ns. Several different methods for performing this synchronization will be reported in a future report.

VII. Conclusion

These systems allow frequency standards to be available at several sites without the high cost of separate frequency standards. One hydrogen maser could provide a frequency reference for all of Goldstone at a fraction of the cost of individual masers. An additional advantage of such a system will be for Very Long Baseline Interferometry experiments. Using this system the same LO and time tick will be available at both stations, eliminating the problem of frequency skew between standards and improving some types of tracking data (reference). In the future it may be possible to use such a system in conjunction with a communications satellite to provide the same clock at all the DSN stations throughout the world.

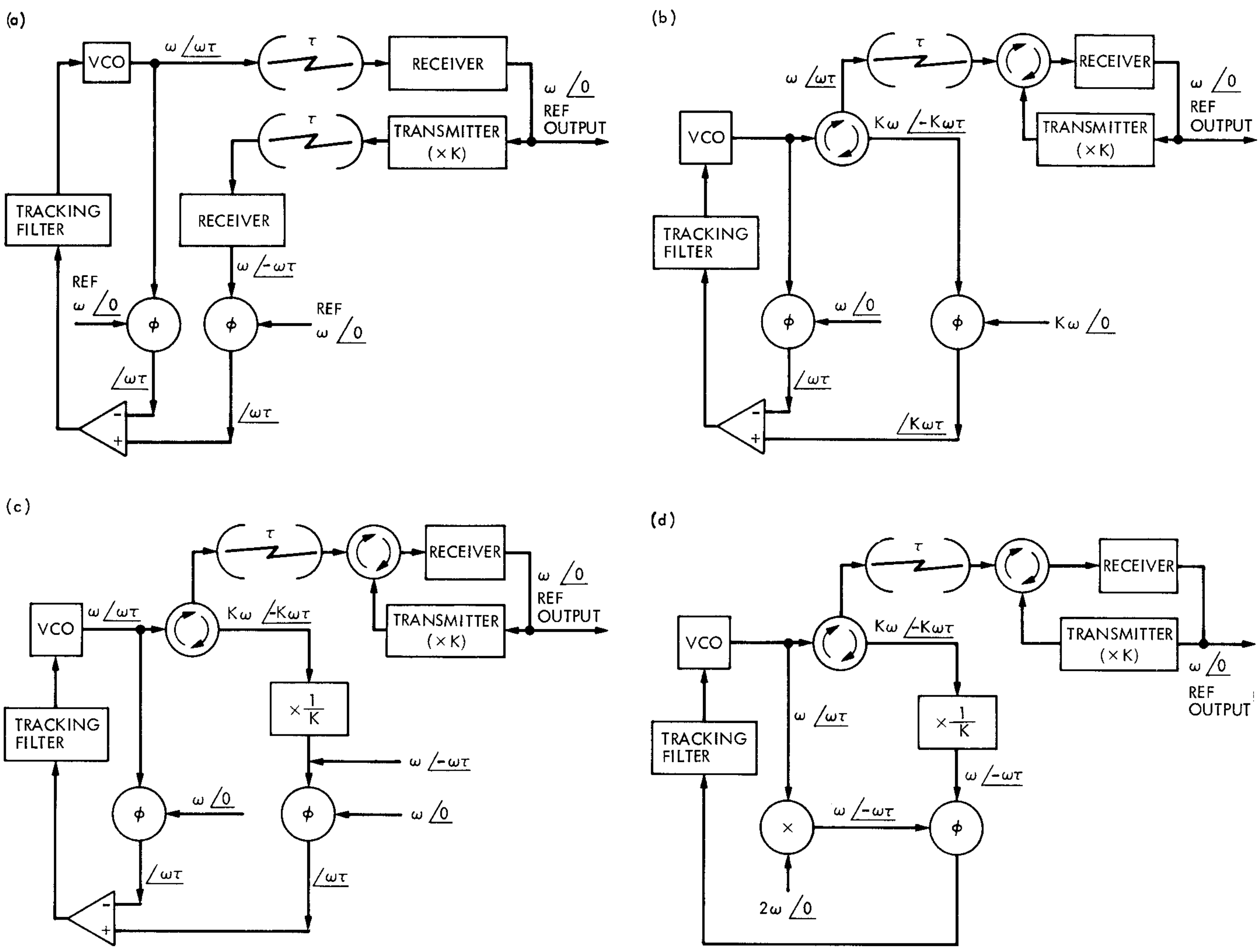


Fig. 1. Conceptual frequency distribution systems

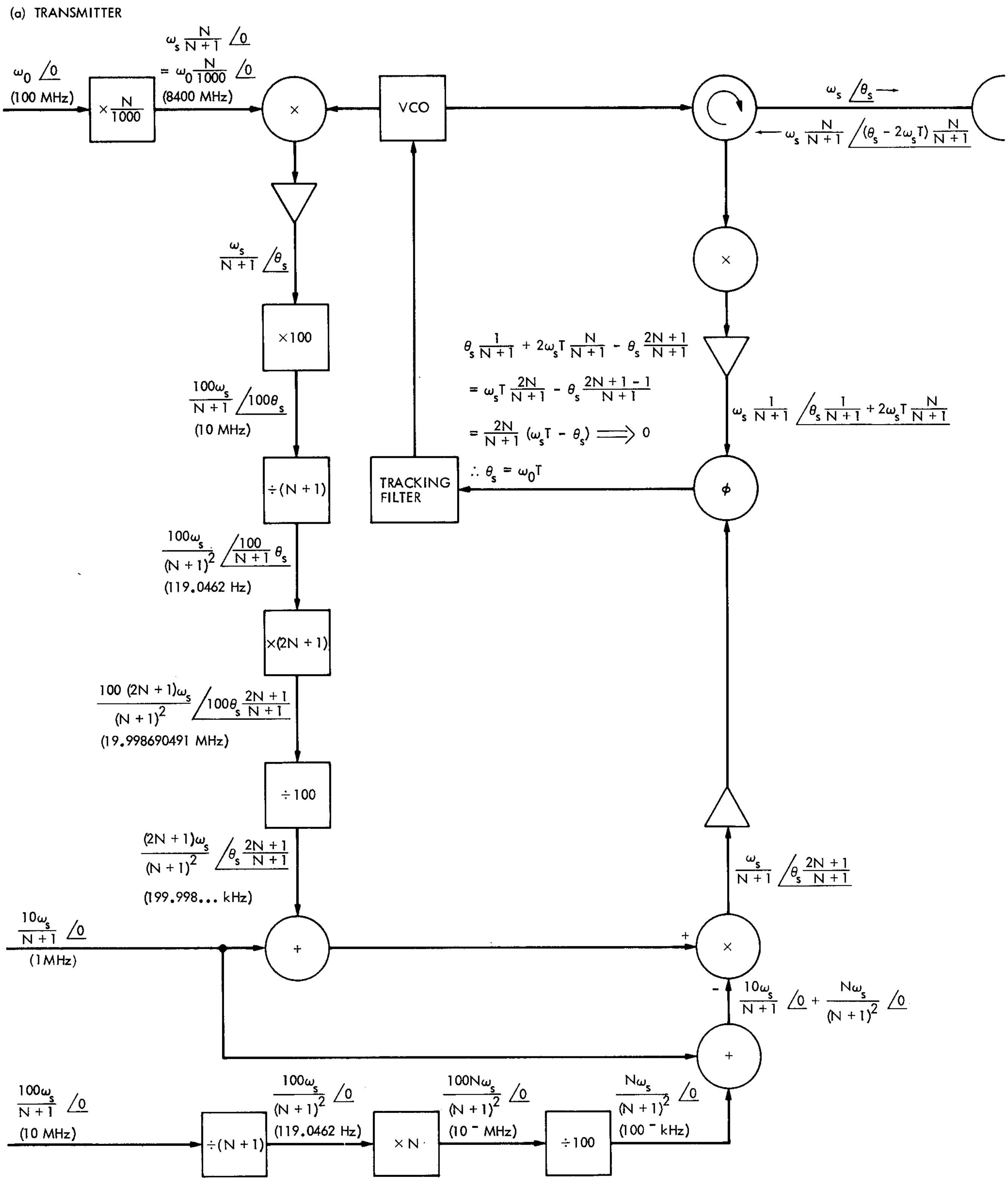


Fig. 2. Exact synthesis system

(b) RECEIVER

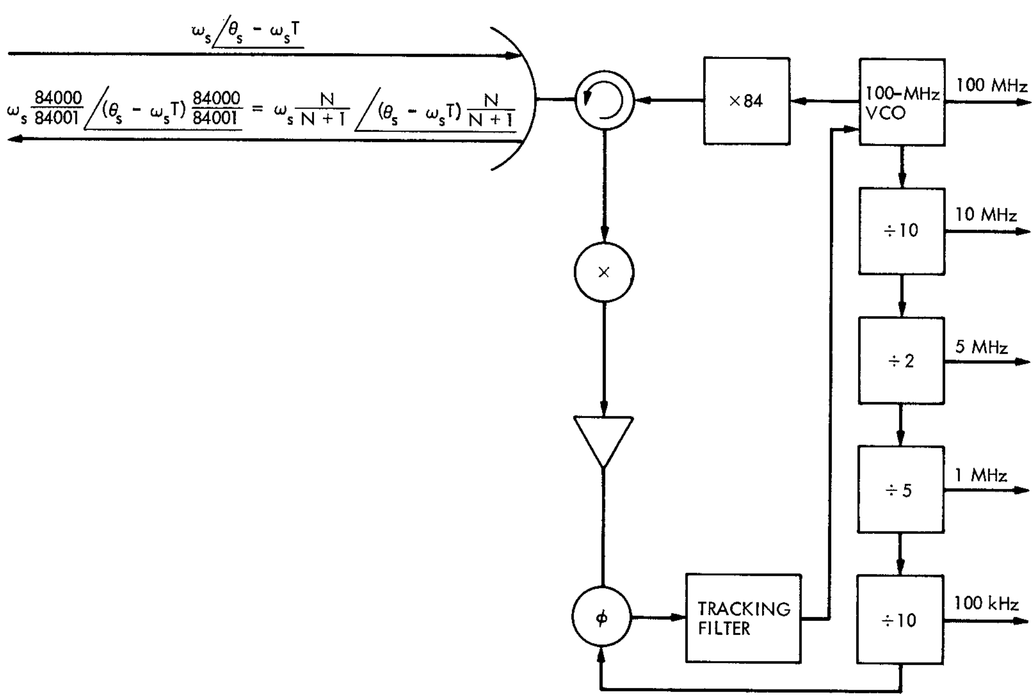
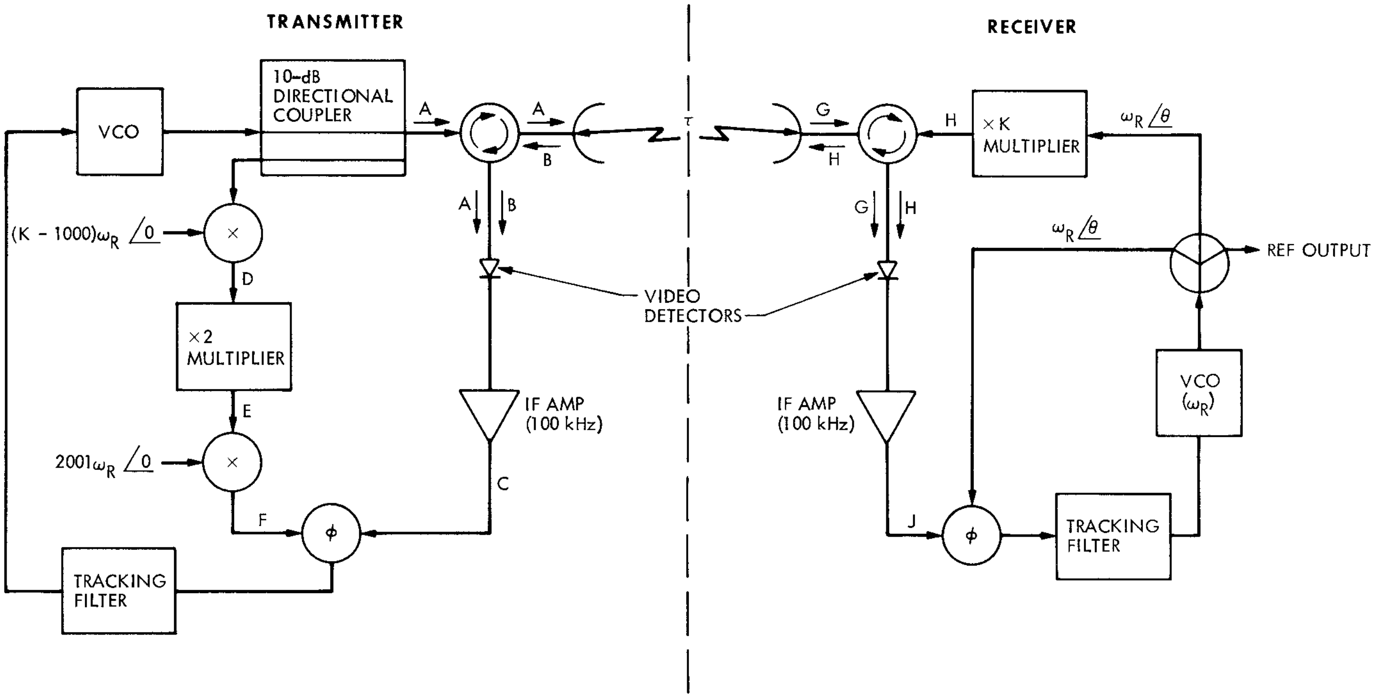


Fig. 2 (contd)



TRANSMITTER PHASES:

(A) $(K+1)\omega_R \angle \phi$

(B) $K\omega_R \angle -2K\omega_R\tau + \frac{K\phi}{K+1}$

(C) $(A) - (B) = (K+1)\omega_R \angle \phi - \left[K\omega_R \angle -2K\omega_R\tau + \frac{K\phi}{K+1}\right]$

$= \omega_R \angle \phi - \frac{K}{K+1}\phi + 2K\omega_R\tau$

(D) $(K+1)\omega_R \angle \phi - \left[(K-1000)\omega_R \angle 0\right] = 1001\omega_R \angle \phi$

(E) $2(D) = 2002\omega_R \angle 2\phi$

(F) $2002\omega_R \angle 2\phi - 2001\omega_R \angle 0 = \omega_R \angle 2\phi$

THE PHASE DETECTOR AND LOOP FORCES (F) AND (C) TO BE EQUAL:

$$\omega_R \angle 2\phi = \omega_R \angle \phi - \frac{K}{K+1}\phi + 2K\omega_R\tau$$

SOLVING FOR PHASE PORTION OF EXPRESSION:

$$2\phi = \phi - \frac{K}{K+1}\phi + 2K\omega_R\tau$$

$$\phi = \left(\frac{2K}{2K+1}\right)(K+1)\omega_R\tau$$

RECEIVER PHASES:

(G) $(K+1)\omega_R \angle -(K+1)\omega_R\tau + \phi$

(H) $K\omega_R \angle K\theta$

(J) $\omega_R \angle -K\theta - (K+1)\omega_R\tau + \phi$

BUT $-K\theta - (K+1)\omega_R\tau + \phi = \theta$

$$\therefore \theta = \omega_R\tau + \frac{\phi}{K+1} \qquad (1)$$

IDEALLY ϕ SHOULD EQUAL $(K+1)\omega_R\tau$ (OBTAINED BY SETTING θ IN (1) TO 0 AND SOLVING FOR ϕ). THEREFORE, ERROR $= 1/(2K+1)$.

WITH THE JPL APPROXIMATE SYSTEM $K = 8.4 \times 10^4$. THE RESULTANT ERROR IS 5.95×10^{-6} YIELDING A CORRECTION OF 1.68001×10^5.

Fig. 3. Approximate synthesis system